

ULTRASONIC EVALUATION OF THERMAL DEGRADATION IN ADHESIVE BONDS

Shyh-Shiuh Lih and Ajit K. Mal
Mechanical, Aerospace and Nuclear Engineering Department
University of California, Los Angeles, CA 90024

Yoseph Bar-Cohen
Jet Propulsion Laboratory
Pasadena, CA 91109

INTRODUCTION

The critical role played by adhesive bonds in lap joints is well known. A good knowledge of the mechanical properties of adhesive bonds in lap joints is a prerequisite to the design and reliable prediction of the performance of these bonded structures. Furthermore, the lap joint may be subject to high-temperature environments in service. Early detection of the degree of thermal degradation in adhesive bonds is required under these circumstances. A variety of ultrasonic nondestructive evaluation (NDE) techniques can be used to determine the thickness and the elastic moduli of adhesively bonded joints [1-4]. In this paper we apply a previously developed technique based on the leaky Lamb wave (LLW) experiment to investigate the possibility of characterizing the thermal degradation of adhesive bonds in lap joints. The degradation of the adhesive bonds is determined through comparison between experimental data and theoretical calculations.

THEORY AND EXPERIMENTAL SETUP

The LLW technique is based on an oblique insonification of the bonded specimen immersed in water [5]. When a transducer insonifies a test part at an oblique angle, the wave is reflected as well as mode converted to induce guided waves in the specimen. Certain characteristics of the guided waves are strongly influenced by the properties of the bond. We have carried out a coordinated theoretical and experimental program of research in an effort to determine the relationship between the properties of the adhesive and the measurable properties of the guided waves. We have been able to demonstrate that a careful analysis of guided wave data can give accurate estimates of the degradation in thickness and elastic properties of the adhesive in a variety of bonded systems.

The theory of guided wave propagation in bonded, layered solid is well established. The general theoretical model is sketched in Fig. 1 where a layered plate bonded by adhesive layers is immersed in water. The m th layer ($m=1, 2, \dots, N$) is assumed to be bounded by the planes $z = z_m$ and $z = z_{m+1}$. The density, p-wave speed and S-wave speed in the m th layer are ρ_m , α_m , and β_m , respectively. A plane acoustic wave is launched on the top surface of the plate and the reflected wave field is to be determined. Assuming all field variables to be independent of y , the displacement and stress components in the structure can be expressed in the form [6, 7],

$$\{u_x, u_z, \sigma_{xz}, \sigma_{zz}\} = \{S(z)\} e^{i(kx - \omega t)} \quad (1)$$

where ω is the circular frequency, and $\{S(z)\}$ is the column vector of the z -dependent parts of the displacement and the stress vectors. The wave number k is defined by

$$k = \frac{\omega}{\alpha_0} \sin \theta \quad (2)$$

$$\{S_m(z)\} = [Q_m][E_m(z)] \begin{bmatrix} C_m^+ \\ C_m^- \end{bmatrix} \quad (3)$$

where θ is the incident angle and α_0 is the acoustic wave speed in water. The displacement-stress vector $\{S_m(z)\}$ in the m th layer has the general form where $\{C_m^+\}$, $\{C_m^-\}$ are constant vectors corresponding to the downgoing and upgoing waves, respectively. The matrices $[Q_m]$ and $[E_m(z)]$ can be expressed in terms of the frequency, material properties, and the wavenumber of the m th layer; their elements can be found in [6]. Using the continuity conditions across the m th interface,

$$\{S_m(z_m)\} = \{S_{m+1}(z_m)\} \quad (4)$$

and the traction free boundary conditions at top and bottom of the structure, a global matrix can be assembled as a linear system

$$[Q]\{C\} = \{B\} \quad (5)$$

for the calculation of the unknown constant vectors $\{C^*\}$. The phase velocity V of the guided leaky Lamb waves in the plate can then be calculated from the condition of nontrivial solution of the system:

$$G(k, f) = \text{Det}[Q] = 0 \quad (6)$$

with $V = 2\pi f/k$. Equation (6) is the dispersion equation of the guided waves. The details of this so called global matrix formulation can be found in Mal [6]. The model can be used to calculate the guided wave speed within a lap joint which consists of two plates bonded together by an adhesive layer.

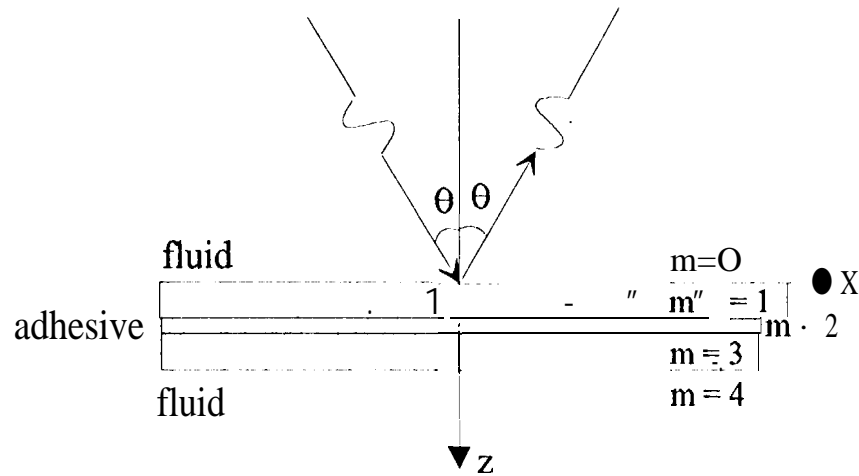


Figure. 1. Geometry of a bonded plate immersed in water.

It is well known that the minima in the reflected amplitude spectra are associated with the generation of the leaky guided waves in the specimen. Thus the possible guided wave modes at various incident angles can be represented by the dispersion curves. The ultrasonic experiment used to measure the guided wave speed is based on an oblique **insonification** with the test specimen immersed in water in a pitch-catch arrangement as shown in Fig. 2. For a given angle of incidence, the amplitude spectra of the reflected waves contain sharp minima; their locations on the frequency axis can be used for accurate measurement of the phase velocity of the leaky guided waves in the laminate. The velocity data can be displayed as dispersion curves, i.e., the phase velocity of the different modes plotted vs. frequency. A detailed description of the experimental setup can be found in [5].

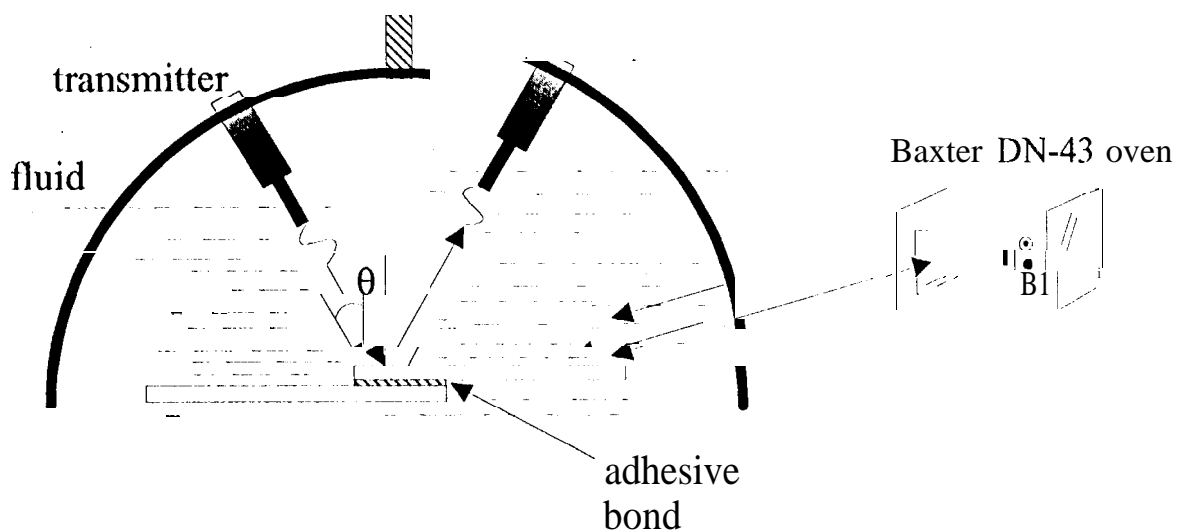


Figure. 2. The leaky Lamb wave setup for inspection of heat damaged adhesive joints.

CHARACTERIZATION OF THERMAL DEGRADATION OF ADHESIVE BONDS IN LAP JOINTS

Two lap joint specimens were used in this study. One is made out of aluminum and the other of titanium. Each specimen was placed in a Baxter oven and heated at 220°C for one hour. The LLW dispersion curves in the bonded region were determined before and after heating for each specimen. The dispersion curves away from the bonds were also measured for reference. The results are as follows.

a) Aluminum lap joint

The Young's modulus E , shear modulus μ , thickness h and density ρ of the aluminum plates used in the calculations are listed in Table 1. The elastic constants of the adhesive joint were obtained through inversion of the phase velocity data from the LLW experiment. Fig. 3 shows the comparison between the measured and calculated dispersion curves of the specimen in the bonded region before heat treatment. The excellent agreement between the measured and calculated results indicates that the inverted elastic constants of the adhesive joint are accurate. Fig. 4 shows the measured dispersion curves of the aluminum lap joint in the bonded region before and after heat treatment. It can be seen that the dispersion curves in the bonded region are significantly different before and after heat treatment, while there is no change in them at the point away from it (Fig. 5). This implies that the change in the dispersion curves comes from the degradation of the adhesive bond. We now use the measured dispersion curves to characterize the degradation of the adhesive joint. Fig. 6 shows the measured and calculated dispersion curves of the specimen in the bonded region after heat treatment where the Young's modulus and shear modulus of the adhesive joint used in the calculation are changed to 0.89 GPa and 0.30 GPa, respectively. Thus the heat treatment appears to cause a significant reduction in both moduli of the adhesive bond.

Table 1. Properties of the aluminum specimen,

| | E (GPa) | μ (GPa) | h (mm) | ρ (g/cm ³) |
|-----------------------------------|-----------|-------------|----------|-----------------------------|
| Aluminum | 72,47 | 26.91 | 1.53 | 2.8 |
| Adhesive bond (before heating) | 2.65 | 0.98 | 0.203 | 1.2 |
| Adhesive bond (after Heating) | 0.89 | 0.30 | 0.203 | 1.2 |

b) Titanium lap joint

The same procedure as in a) is used to characterize a titanium lap joint with material properties listed in Table 2. It should be noted that the adhesive bond in titanium is different from that in the aluminum specimen mentioned above. Fig. 7 shows the measured dispersion curves in the bonded region for the titanium lap joint in the bonded region before and after heat treatment. It can be seen that the dispersion curve are significantly different before and after heat treatment. From the reference

dispersion curves to characterize the degradation of the adhesive joint as in the case of aluminum. Fig. 8 shows the measured and the calculated dispersion curves for the specimen in the bonded region after heat treatment, where the Young's modulus and shear modulus of the adhesive joint used in the calculation are 4.45 GPa and 1.73 GPa, respectively, again indicating a significant reduction in their values due to the heat treatment. In general there are more modes in the calculated dispersion curves than the experimental data. This is due to the fact that certain guided wave modes are so close that the corresponding minima in the reflection spectrum merge (Fig. 9) in the experiment. The separation of these individual mode is difficult in the current experimental setup.

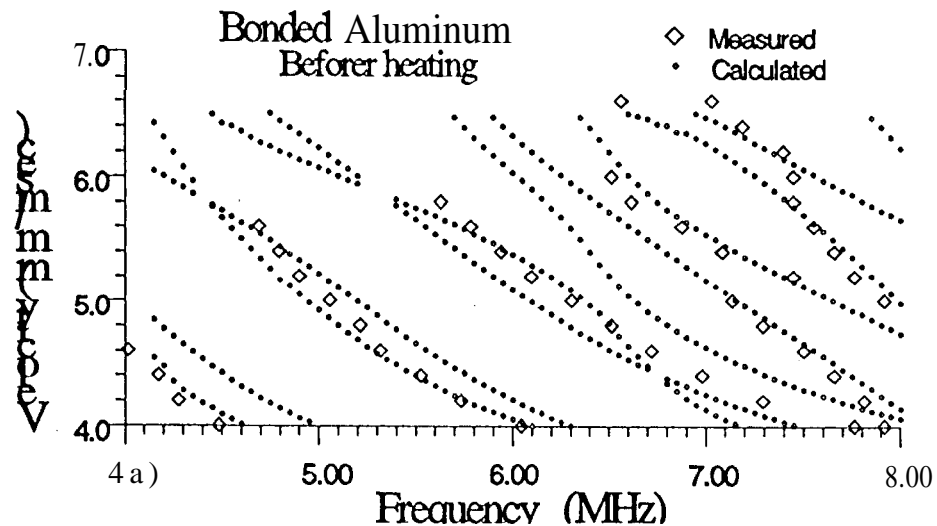


Figure 3. Comparison between measured and calculated dispersion curves for an aluminum lap joint before heat treatment.

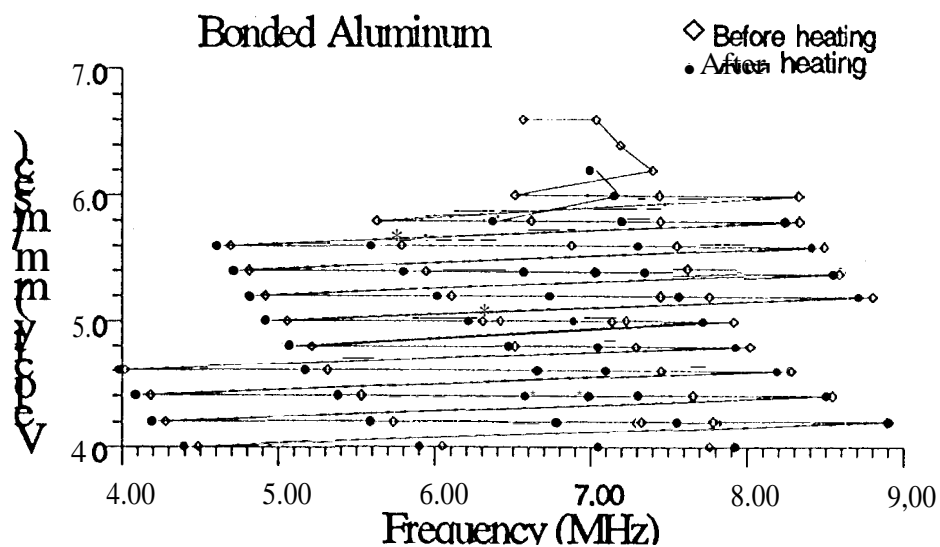


Figure 4. Lamb wave dispersion curves in bonded aluminum before and after heat treatment.

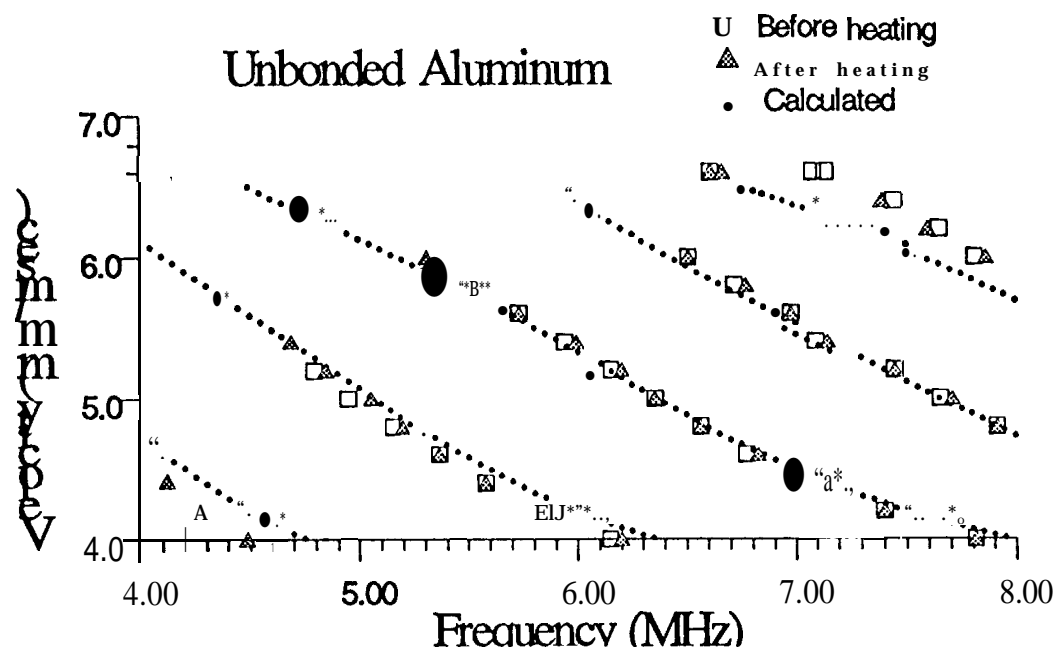


Figure. 5. Lamb wave dispersion curves for a 1.53 mm thick aluminum plate.

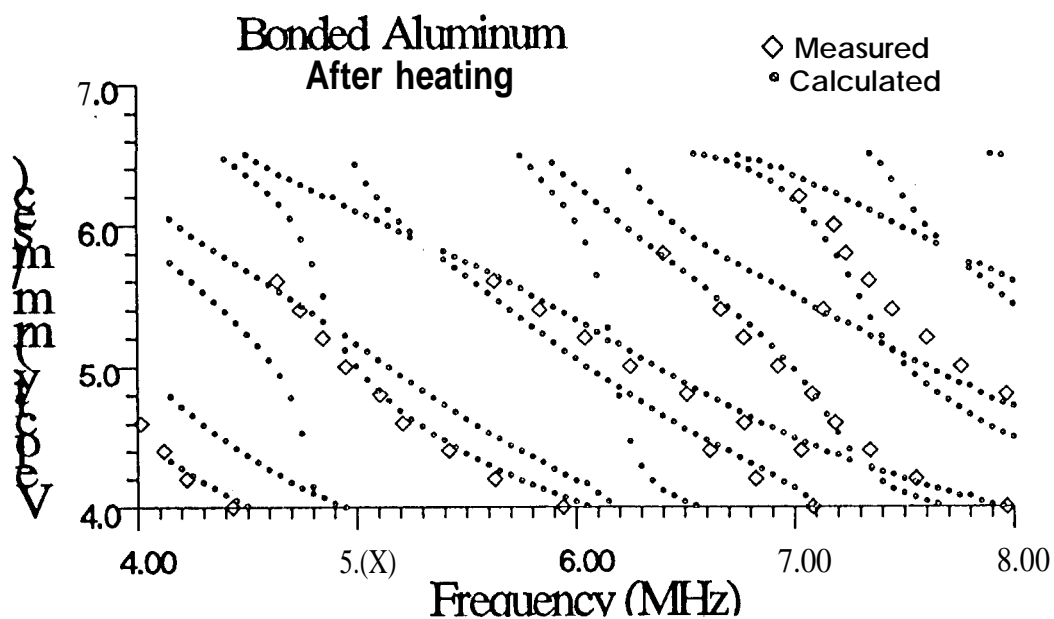


Figure. 6. Comparison between measured and calculated dispersion curves for an aluminum lap joint after heat treatment.

Table 2. Properties of the titanium specimen

| | E (GPa) | μ (GPa) | h (mm) | ρ (g/cm ³) |
|-----------------------------------|---------|-------------|--------|-----------------------------|
| Titanium | 85.75 | 33.00 | 1.80 | 4.96 |
| Adhesive bond (before heating) | 6.09 | 2.35 | 0.127 | 1.2 |
| Adhesive bond (after heating) | 4.45 | 1.73 | 0.127 | 1.2 |

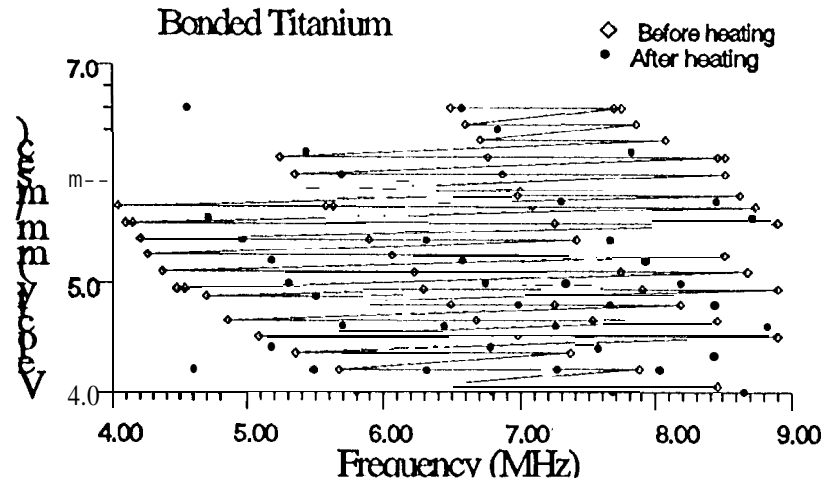


Figure. 7. Lamb wave dispersion curves in bonded titanium before and after heat treatment.

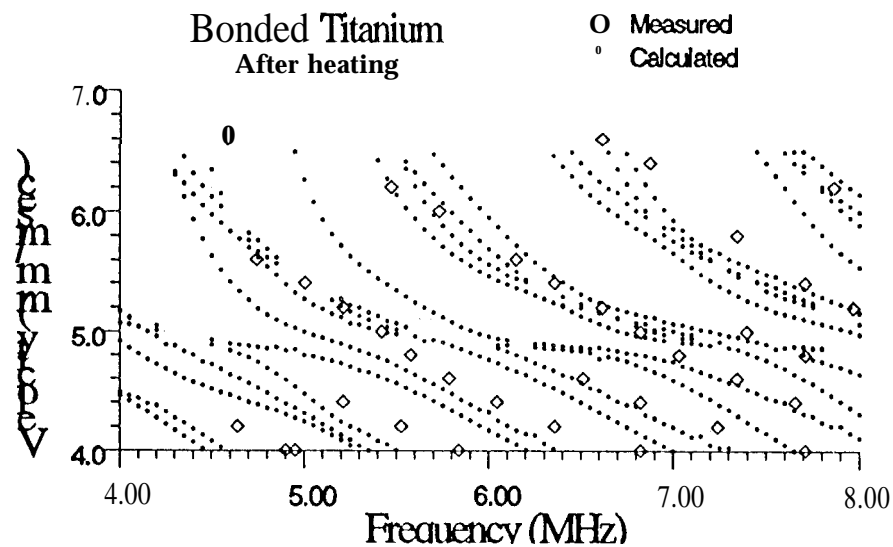


Figure. 8. Comparison between measured and calculated dispersion curves for a titanium lap joint after heat treatment.

CONCLUDING REMARKS

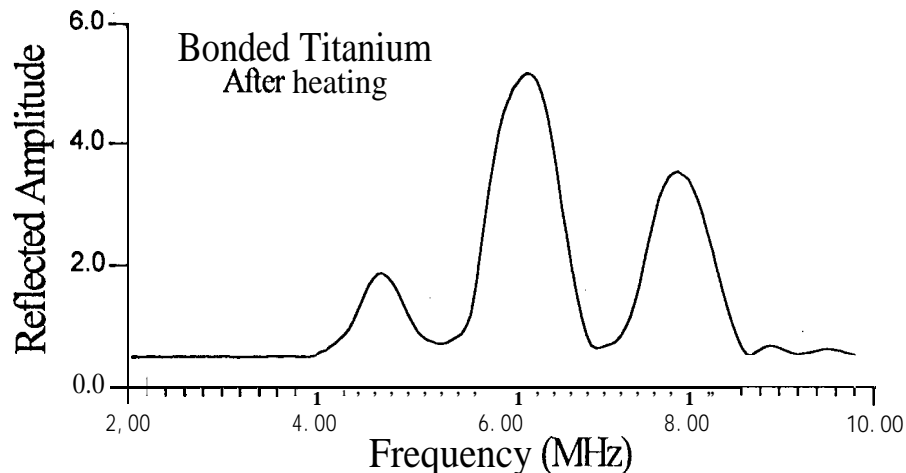


Figure. 9. A typical reflected amplitude spectrum for a titanium lap joint after heat treatment ($\theta = 16.6^\circ$).

Thermal degradation of adhesive bonds in lap joints is studied by means of an ultrasonic nondestructive evaluation technique. The influence of the thermal degradation of adhesive bonds on the phase velocity of guided waves in bonded lap joints is investigated. The results show that in both bonded aluminum and titanium lap joints there is a significant difference in the dispersion curves for heat damaged and undamaged specimens in the bonded region. The degradation in the elastic properties of the adhesive bonds is determined through comparison between experimental data and theoretical calculations.

ACKNOWLEDGEMENT

This research was supported by the AFOSR under grant F49620-93-1-0320 monitored by Dr. Walter Jones. The experimental part of the study that was carried out at the Jet Propulsion Laboratory (JPL), California Institute of Technology (Caltech), was performed under a contract with the National Aeronautics and Space Administration (NASA).

REFERENCES

1. R. J. Botsco and R. T. Anderson, *Adhesive Ages*, p. 22 (1984).
2. J. M. Baik and R. B. Thompson, *J. Nondestruct. Eval.*, 4, p. 77 (1984).
3. C. C. H. Guyott and P. Cawley, *NDT International*, 21, p. 873 (1988).
4. T. Kundu, *J. of Appl. Mech.*, 59, p. 54 (1992).
5. Y. Bar-Cohen, *Solid Mechanics Research for Quantitative NDE*, J.D. Achenbach and Y. Rajapakse (Eds.), p. 197 (1987).
6. A. K. Mal, *Int. J. Engr. Sci.*, 26, p. 873 (1988).
7. A. K. Mal, P.-C. Xu., and Y. Bar-Cohen, *J. Engr. Material and Tech.*, 112, p. 255 (1989).